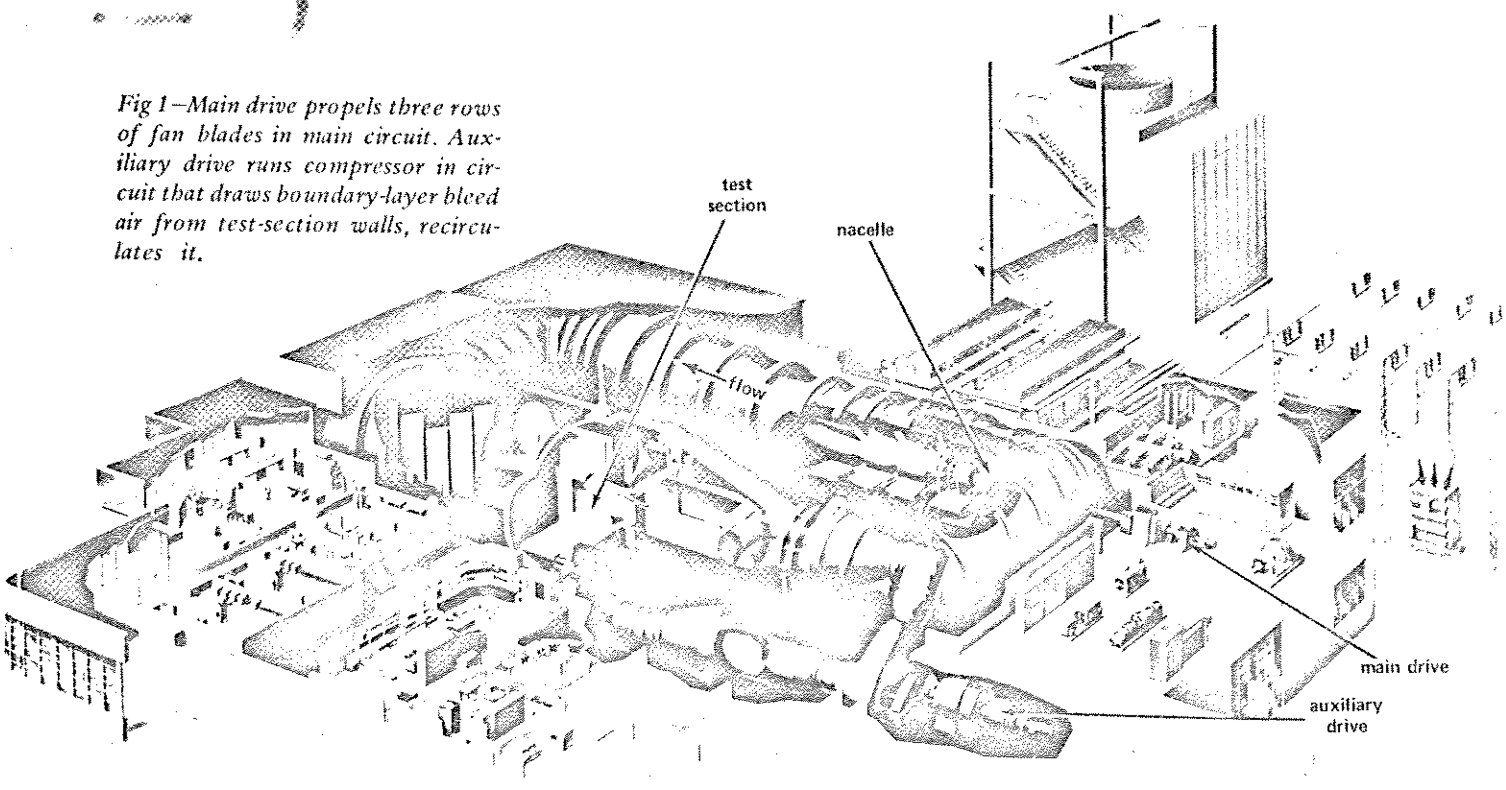
Driving the 1000-mph wind in Calspan's tunnel

Fig 1—Main drive propels three rows of fan blades in main circuit. Auxiliary drive runs compressor in circuit that draws boundary-layer bleed air from test-section walls, recirculates it.



Power
Transmission
Design MARCH 1973

Driving the 1000-mph wind in Calspan's tunnel

By Clement S. Daly, P.E. The Calspan Corp. (formerly Cornell Aeronautical Laboratory, Inc.) 8-ft transonic tunnel produces air speeds to 1000 mph, but it takes more than 26,000 hp in two main drive systems to do it. And the tunnel is a zero-efficiency machine, so it must get rid of the heat produced by all that power.

When you apply sound principles in selecting drive components, your installation will be around for years. Most of our articles deal with installations that have gone on line recently, but to emphasize the endurance of well designed systems, we bring you Mr. Daly's story of the drives in Calspan's transonic tunnel.

The tunnel was upgraded for higher-velocity tests in 1956, and improved further in 1965. Calspan saved old drive components wherever feasible. And designers put a lot of thoughtful head-scratching into drive modifications to keep maintenance men from pulling their hair. On this and the following page, Mr. Daly shows you through the test facility. Then on page 37, you'll learn the how and why of the 12,250-hp main drive; on page 40, the 14,250-hp auxiliary drive.

Wind tunnels can cover a wide range of testing from basic research to test theory to full-scale airplane testing. Calspan's transonic tunnel (Fig 1) undertakes some basic research, but most testing is on scaled-down models of real aircraft, missiles, and space vehicles. The variable-density, continuous-flow, closed-circuit tunnel, 386 ft long around the circuit centerline, is one of the nation's most productive in transonic testing (testing above or below the speed of sound).

The tunnel can produce air speeds from near zero to 1000 mph (Mach 1.35) at sea level. Compressors and vacuum pumps can change the air density in the tunnel from that of 3-1/4 times sea-level pressure to simulate high-altitude flight.

The tunnel is a pressure vessel of circular cross section, laid out in a

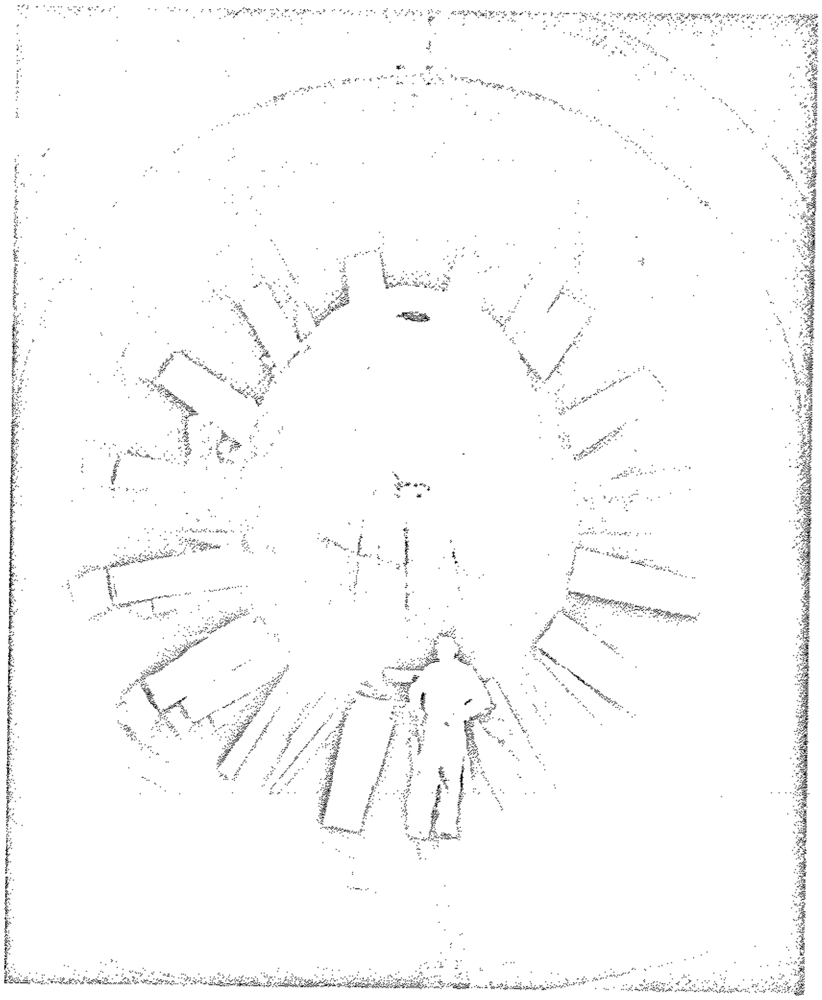


Fig 2—Nacelle section houses drives and bearings of three adjustable-pitch fan-blade hubs in tunnel's main section. Three 10-ft-dia hubs each mount 16 blades, 60 in. long by 15 in. wide. Tunnel dia is 21-1/2 ft at nacelle section. Fans can input 12,250 hp. Technician stands beneath downstream fairing.

rectangular pattern, and of diameter varying from 21-1/2 ft at the nacelle section (Fig 2) to 31-1/2 ft at the largest cross section.

A main drive and an auxiliary drive help move the air past the model. Two main drive motors in tandem turn three rings (hubs), each mounting 16 variable-pitch fan blades in the tunnel's main circuit (Fig 2). Blades are 15 in. wide and 60 in. long. The motors together can deliver 12,250 hp continuously. See page 37 for details of the main drive.

The auxiliary drive powers a pumping system which recirculates some air from the test section. Air slowed by friction at the tunnel walls is drawn off into a plenum chamber through perforations in the test-section wall. An axial-flow compressor accelerates the plenum air (boundary-layer bleed) and pumps it back into the main flow of the tunnel. Two motors in tandem can deliver 14,250 hp continuously to the auxiliary pumping system. See page 40 for details of the drive.

No work—A closed-circuit wind tunnel is essentially a zero-efficiency machine. It circulates air but does no useful work. It converts the total energy input (electrical) into heat and the heat must be dissipated at the input rate to prevent uncontrolled temperature rise in the tunnel.

The tunnel's cooling system holds the temperature rise of the circulating air to no more than 40 F. The system pumps 8000 gpm of water through 80 radiators in the widest point of the tunnel and through two additional banks of radiators in the auxiliary system.

From the radiators, the system pumps the heated water to the top of a 40-ft-high cooling tower, where it drips over a latticework of redwood slats. An alternative cooling arrangement has water spraying into the air through nozzles in three forced-air cooling towers. Evaporation cools the water by 18 to 20 F.

The cooling system draws 80 to 100 gpm of makeup water to replace losses. The largest loss comes from evaporation.

Support equipment for the wind tunnel includes four 150-hp vacuum pumps, three 100-hp vacuum pumps and four 150-hp low-pressure air compressors for air-density control; a 1000-hp, 3000-psi air compressor for charging the air-storage system; air storage, drying, and distribution systems, and a large power-distribution system. All equipment is operated from a main console in the wind-tunnel control room, where remote sensing instruments display total information from the test section and supporting wind-tunnel equipment.

The test section, where the model mounts in the air stream, can be sealed from the main tunnel by closing gates and applying air-inflated collapsible seals. This isolates the test section to allow model changes without affecting air density in the tunnel.

Until 1956, the wind tunnel handled only subsonic-flow tests. Then, Calspan modernized it for transonic testing. Power input (overload rating) nearly doubled for the main drive system, and the auxiliary pumping system was added. The following pages show how Calspan came up with the present drives.

Main drive

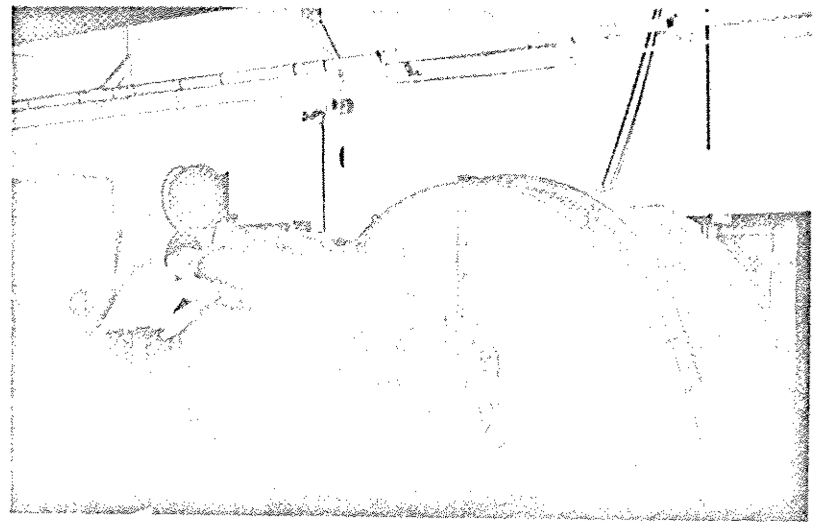


Fig 3—Technician inspects commutator of 1250-hp d.c. main-drive starting motor. It brings 11,000-hp synchronous motor (at right) to speed. Motors in tandem could supply 19,850 hp for a 10-min test. D.c.-motor power comes from Ward-Leonard control.

The present main-drive system includes two motors in tandem, a floating-shaft coupling, a long drive shaft with bearings, and a disengaging shear-pin coupling. The main drive powers all three fan hubs.

Before modernization, the system contained a 2-motor drive with a capacity of 10,250 hp. It powered two hubs with 16 blades each. The large motor was a wound-rotor induction motor that developed full power at 570 rpm. The replacement drive consists of a synchronous motor and a d.c. motor (Fig 3). The 600-rpm synchronous motor's ratings are

- 11,000 hp for continuous running
- 13,250 hp for 2 hr
- 18,000 hp for 10 min

Outside air force-cools the motor.

The shaft of a 0-650 rpm d.c. motor connects to the synchronous motor's shaft by means of a rigid coupling. The d.c. motor's ratings are

- 1250 hp for continuous running
- 1450 hp for 2 hr
- 1850 hp for 10 min

The force-cooling system that serves the synchronous motor cools the d.c. motor, too.

Because wind-tunnel tests are not continuous but may require peak power for only short durations, the motors run often at overload (limited-time) ratings, both to start the main drive from standstill and to obtain maximum air flow with both motors driving.

D.c. motor—The d.c. motor's uses include

- bringing the main drive to speed
- precisely setting the phase and frequency to synchronize the synchronous motor at 600 rpm
- contributing its full share of the power to the main drive shaft in tandem with the synchronous motor
- providing regenerative braking when the main drive stops

To start the main drive, the operator sets fan-blade pitch (blade angle) to flat pitch (minimum aerodynamic drag). This blade setting calls for the least power to turn the hubs. However, rotation at flat pitch takes some power because of the turbulence set up by the twist in the blades. That power depends on tunnel air density.

The rotational inertia (WK^2) of the fan system, shafting, couplings, and motors is 1,063,000 lb-ft^2, and the time to bring the main drive to 600 rpm is about 6 min for a 160% load on the d.c. motor.

The d.c. motor is part of a Ward-Leonard motor-generator control system with electronic control and tachometer feedback. The m-g set consists of a 2600-hp synchronous motor driving an 1100-kw d.c. generator. The generator had served as a 1375-hp d.c. drive motor on a World War II submarine. Main drive starting and synchronizing is under fully automatic control.

Synchronous motor—The 4800-volt, 3-phase, 60-Hz synchronous motor (Fig 4) connects in tandem to the d.c. motor and supplies 90% of the main drive's power after synchronization at 600 rpm. Calspan selected a synchronous motor rather than an induction motor or wound-rotor motor because fan-

Fig 4—Main-drive synchronous motor dismantled. Tapered shaft (right) on 12-pole rotor accepts one hub of floating-shaft coupling to tunnel shaft. Synchronous motor means tunnel air flow rate depends only on blade pitch.

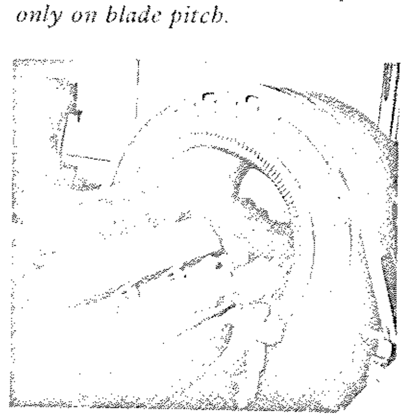


Fig 5—Both ends of 30-ft shaft are tapered for mounting the coupling hubs. Reworking to add more bolt holes was done with shaft in place.

blade pitch precisely controls wind velocity if the blades run at constant speed.

Also, start-up power in the d.c. motor is adequate. Thus, the large drive motor (the synchronous motor) does not have to deliver power until the main drive reaches full speed. The fan system is fully utilized with a synchronous motor for a prime mover instead of an induction motor. Why? Because shaft power increases with overload with no speed drop until it reaches the motor's pullout point. Moreover, shaft and coupling ratings are in terms of hp/100 rpm. The higher the speed, the higher the power rating. Thus, in an extreme overload, the safety factor of shaft and couplings is greater for a synchronous motor at 600 rpm than for an induction motor at, say, 540 rpm.

No whiplash—A stringent requirement of the synchronous motor control: The motor must be synchronized at the lowest possible step-input torque to the shaft. Why? To prevent high stress in the necks of the fan blades. Full-speed elapsed time and the number of starts and stops limit blade life.

The synchro-verifier senses the incoming line voltage and the voltage of the synchronous motor acting as a generator. The synchro-verifier contacts will close when the two voltages are equal, in phase, and of the same frequency (within limits). If there is a beat frequency across the open circuit breaker that connects motor to line, the synchro-verifier contacts will not close. Then phase angles are within ±3 degrees for 4 sec, the contacts close and the motor's circuit breaker closes automatically.

Motor mounts—The main drive motors mount on a concrete base reaching to the second floor of the power area building, on the tunnel centerline but outside the tunnel (Fig 1). The center core of the concrete base acts as a duct for forced-air cooling to both motors.

The synchronous motor is totally enclosed. Ducts direct its hot-air output to the roof. The d.c. motor (Fig 3) is open at the commutator end and its hot-air output helps in room-temperature control.

Floater—The main drive is fixed on its base, but the tunnel changes position because of variations in temperature and pressure. The drive has its own Kingsbury-type thrust bearing, and each of the three hubs has a self-aligning spherical roller thrust bearing, 18.9-in. OD by 4.3-in. wide, of high load-carrying capacity. Therefore, any axial change in location must be accounted for between the drive and the tunnel. The main drive connects to the tunnel by a special floating-shaft coupling.

The gear-type, dynamically balanced, floating-shaft coupling allows for fan-shaft expansion. It can transmit 24,500 hp at 600 rpm, with 2-1/4-in. axial movement and 1-in. radial misalignment. No thrust transmits through the shaft in either direction.

Main driveshaft—A 30-ft-long hollow steel shaft protrudes just outside the wind-tunnel shell on the main-drive end and extends to the first stage of fan blades. The shaft is 16-in.-OD pipe with a solid forging welded to each end. The forgings are machined for bearing supports. Each forging is tapered along its outer 10 in. with a double key slot for mounting coupling hubs (Fig 5).

These procedures assure adequate shaft balance:

- During fabrication the pipe was corrected for roundness and straightness.
- End forgings were machined all over after welding.
- The pipe was statically balanced with weights at both ends.
- After installation, pipe was dynamically balanced at 600 rpm by weight adjustment at the center of gravity. One steel weight 1-1/4 in. wide by 1-1/4 in. high by 23-1/2 in. long was enough.

The bearing mounts for this 1985-lb shaft are about 27 ft apart. The bearing at the tunnel wall is a sleeve bearing, sealed and babbitt-coated, with a dual lubrication system. One lube system operates when tunnel air density is below atmospheric (vacuum); the other, above.

The bearing at the opposite end of the shaft (inside the tunnel, near the first stage of fan blades) is a self-aligning spherical roller bearing, 18.9-in. OD by 5.1-in. wide. It positions the shaft axially. Thrust load on this bearing is low. The method of fan suspension called for self-aligning bearings. (See "Hubs," below.)

During tunnel modernization in 1956, Calspan evaluated the originally installed shaft and found it to be capable of more than 20,000 hp at 600 rpm if the tapered ends were modified for the new couplings. (See "Couplings," below.) Reworking consisted mostly of adding more bolts in the forging ends, where a pressure plate applies force to the coupling hub. Reworking was done with the shaft in place.

Couplings—Joining the 30-ft hollow shaft and the first stage of fan blades presented a tough design problem because

- Each hub must be mechanically separable, so that it can turn by hand for maintenance (usually, blade replacement).
- The first coupling must transmit total power from the main drive.
- A fail-safe device must locate

between main drive and fan system for personnel safety and equipment protection.

A further complication: The coupling must be assembled in place, with all parts passing through a 12-in. gap between shaft ends. It would be a major task to remove one or both adjacent shafts.

The solution: A gear-type flexible coupling (Fig 6) that meets these specifications:

- quick disengagement
- coupling rating, 25,000 hp at 600 rpm, continuous duty
- shear-pin rating, 22,000 hp (disengagement by shear pin)
- dynamic balance according to MIL STD 167.

The coupling is exactly the same dimensional size as the original coupling, but nitralloy steel with higher hardness (Rc 60) and full-depth gear teeth that increase contact area allow a rating increase from 16,000 to 25,000 hp.

The quick disengagement lets a technician turn the blades by hand for inspection. He removes two

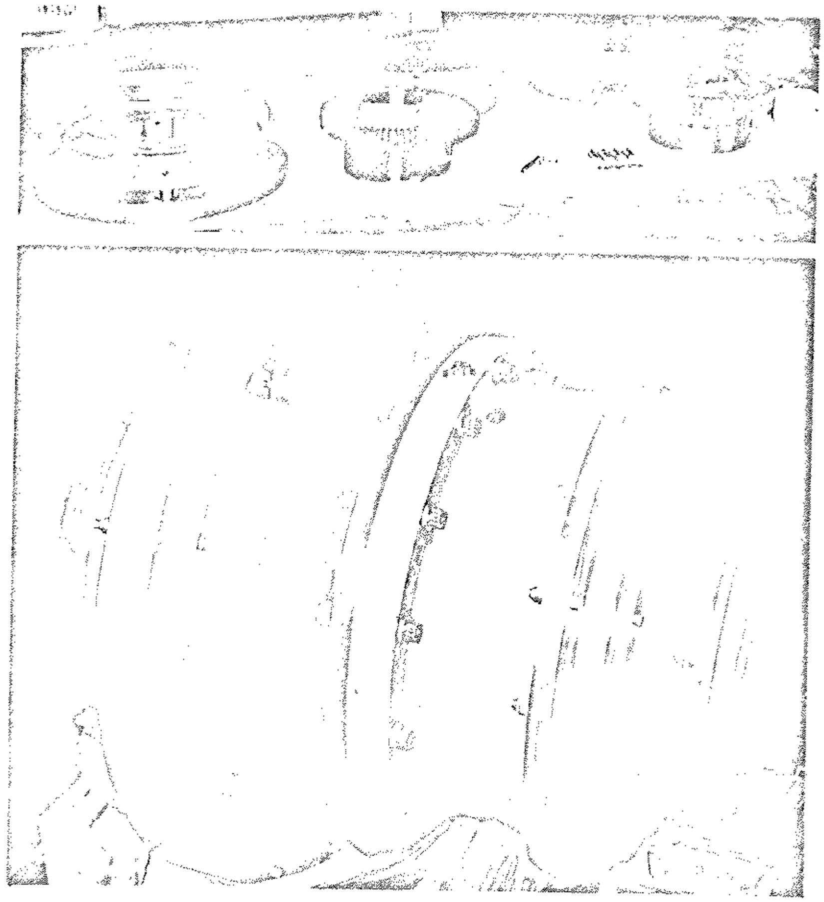
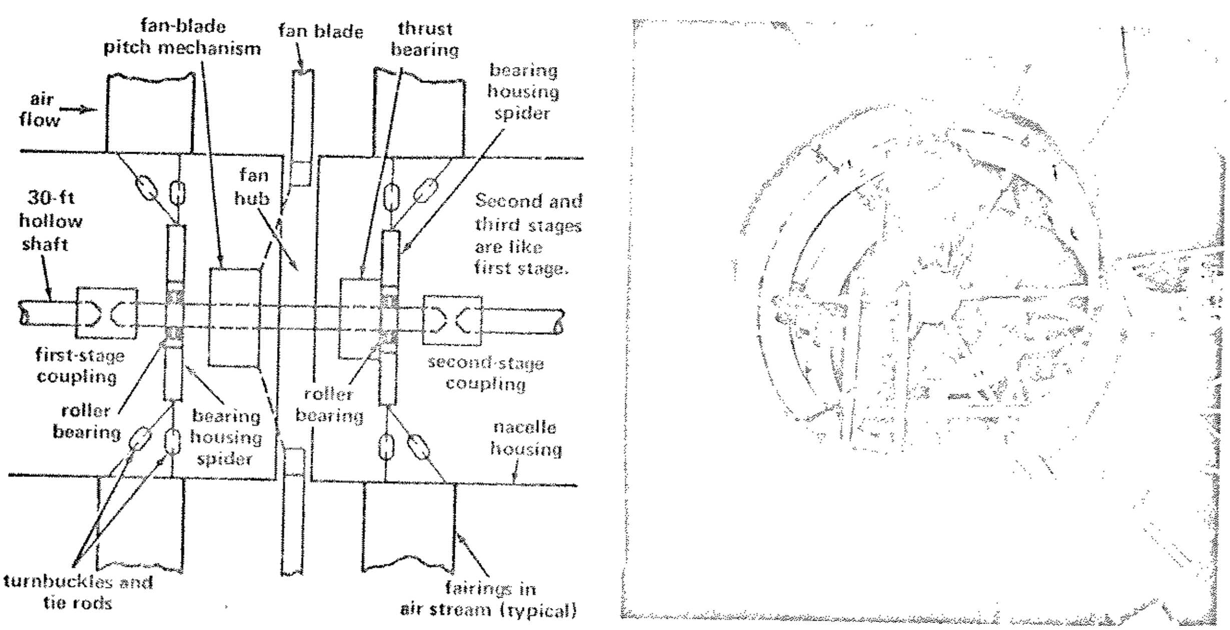


Fig 6—Gear-type, disengaging flexible coupling that connects tunnel drive shaft to first stage. All parts (upper photo) pass through a 12-in. gap for assembly. Alternative would have been moving shafts out of way. Four shear pins (upper photo, lower right) have total rating of 22,000 hp.

Fig 7—Arrangement of fan blade hub and support in first stage. Each stage has identical bearing and coupling system. Turnbuckles align systems. Photo shows a hub under construction.



locking pins, then hydraulically jacks the outer casing to disengage the splines. It takes about 3 minutes. The action is independent of the shear pins.

Hubs—The three identical fan blade hubs each have a disengaging coupling (Fig 7). A hub consists of a shaft pressed into a varying-width disc, the outer periphery of which is 10 ft in diameter with 16 flats machined for fan-blade mounting.

The leading end of the shaft is supported by a self-aligning roller bearing; the trailing end, by a similar bearing and a self-aligning spherical roller thrust bearing. The bearings mount in spiders which are supported in the tunnel on turnbuckles and tie rods. The turnbuckles align all three stages. The nacelle, a metal shroud, encloses the whole mechanism, so only the fan blades are exposed to the air stream. The nacelle fastens to the tunnel shell by means of steel struts inside fairings.

Lubrication and monitoring—A temperature controlled, forced-feed system measures (with pints-per-min accuracy) oil flow to each bearing for lubrication and cooling.

Nozzles spray oil into the bearings and gear pumps scavenge oil from the bearing cavities. No oil is allowed to remain around a bearing, because bearing rollers could cause a pumping action, producing extra heat. Oil from a constant-pressure manifold flows to each bearing through a metering valve. Automatic controls assure constant pressure and flow rate.

A thermocouple spring-loaded to the outer bearing race near the roller contact provides temperature indication and overtemperature protection; so does a thermocouple that measures oil temperature leaving between the bearing races. Oil flow switches, pressure switches, and temperature and pressure gages make up the remainder of the protective equipment. Permanently mounted vibration pick-ups on each bearing monitor vibration continuously throughout the system.

Auxiliary drive

The auxiliary pumping drive system consists of two motors in tandem, couplings, speed increaser, and axial-flow compressor.

Motors—The drive motor requirements:

- adjustable speed, because flow rate relates directly to compressor speed
- high power from 50% to 100% speed
- precise speed control for a given speed
- a starting motor with low starting torque
- a method of rapid deceleration to save time in each shutdown (There are several in an 8-hr period.)

We chose a Ward-Leonard-controlled d.c. starting motor coupled directly to a wound-rotor motor.

Before tunnel modification in 1956, there was no auxiliary pumping system. When Calspan chose a new system for the main drive (page 37), it relocated the original main drive and made it the auxiliary pumping drive. In 1965, Calspan installed a larger wound-rotor motor on the auxiliary drive.

The starting motor is a 1250-hp, 0-650-rpm, d.c. motor, powered by a 1000-kw d.c. generator. A 1450-hp synchronous motor runs the generator.

The d.c. system is capable of a 25% overload for 30 min. With electronic control and tachometer feedback, speed regulation is ±1/4% from half speed to full speed. Regenerative braking is inherent in this type of Ward-Leonard control.

A rigid coupling directly connects the d.c. motor to a 570-rpm, 4800 -volt, 3-phase, 60-Hz wound-rotor induction motor (Fig 8). Wound-rotor motor ratings are

- 13,000 hp for continuous running
- 16,000 hp for 30 min

Liquid ohms—A liquid rheostat, connected across the rings of the wound-rotor motor and controlled by the current in the d.c. loop, provides speed control from 50% to 100% speed. A liquid rheostat is an adjustable resistor with an electrolytic solution as the resistor element.

In designing the wound-rotor motor, Calspan had to consider carefully the demand of high power in the overload range at reduced speeds. The designed the secondary (rotor) resistance for continuous service and 30-min service so that it dissipates the heat from operation at reduced speed, from frequent acceleration, and from acceleration with a large inertial load. Outside air force-cools the wound-rotor motor and the d.c. motor.

The liquid rheostat must have characteristics compatible with the overload rating of the wound-rotor motor. A set of immersed fixed and movable electrodes conducts current through the solution. A pilot motor changes the distance between electrodes to adjust resistance. Thus, a liquid rheostat in the secondary circuit of a wound-rotor motor can adjust drive speed by adjusting the distance between electrodes. The adjustment controls the external resistance and, thus, the secondary current.

The electrical energy which must be absorbed in the motor's secondary circuit during 50% to 100% speed appears as heat in the liquid rheostat. A liquid-to-liquid heat exchanger removes the heat.

Liquid-rheostat specifications call for a rating 10% above the 30-min rating of the motor, 3500 amp per phase, and a dissipation rate of not less than 7000 hp continuously. Fig 9 and 10 show the liquid rheostat and its electrode drive and control system.

Fig 9 looks down into the liquid rheostat with the electrolytic solution out. The perforated discs are the movable electrodes in plastic cells. All electrodes connect to the shorting bar, and the electrode-drive system moves the bar vertically. A counterweight connects to the shorting bar by means of roller chain draped over sprockets keyed to an idler shaft mounted in ball-bearing pillow blocks. The counterweight keeps the electrode-drive-motor power requirement low and uniform.

The 1/2-hp, 115-volt, d.c. motor powers the electrodes through a speed-reducer and chain-drive system with a total speed reduction ratio of 300:1.

A 6-circuit rotating limit switch mounts on the left of the platform (Fig 9); to its right, a rheostat for electrode position indication and feedback control. A 1:1-ratio chain drive connects rheostat input shaft and counterweight idler shaft. D.c.-motor power comes from the load-sharing system described under "Driving the compressor."

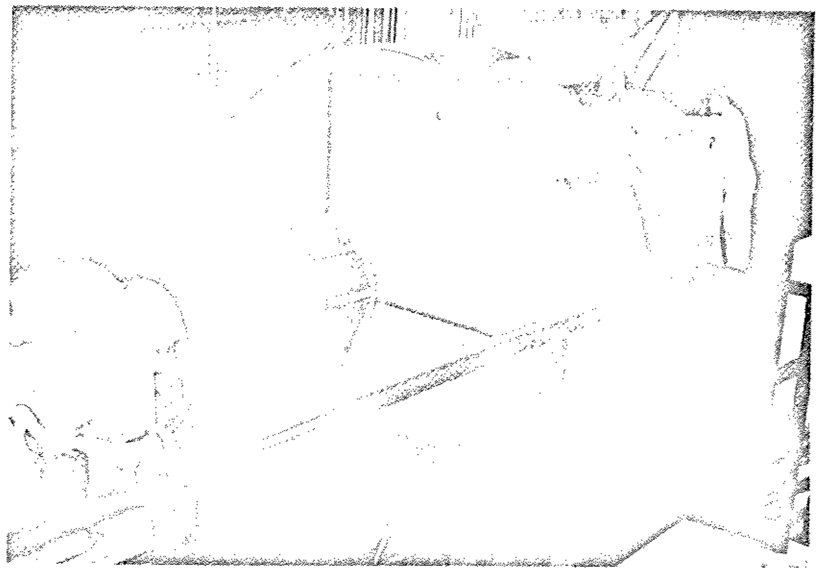


Fig 8—(Right to left): Auxiliary drive starting motor; wound-rotor induction motor; wound-rotor brushes and slip rings (under expanded-metal guard); motor-bearing pedestal (with bearing temperature detector in rectangular box); under cover at right, speed-increaser coupling; in foreground, lube pump driven off speed-increaser high-speed shaft.

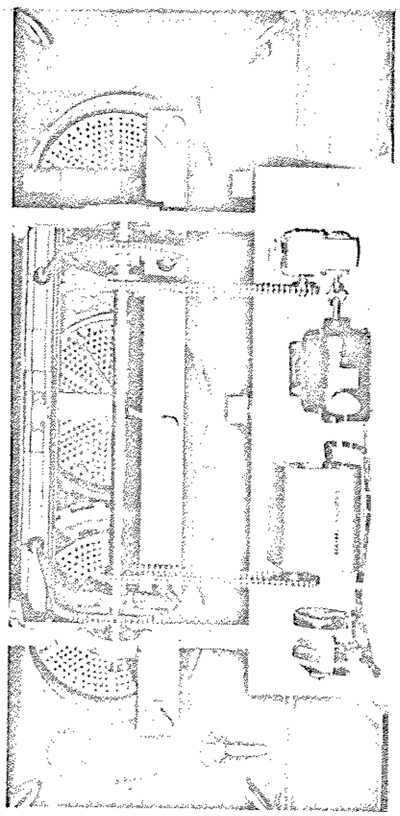


Fig 9—Liquid rheostat from above. Idler shaft supports electrodes, shorting bar, and counterweight. Position sensing and transmitting system (left); electrode drive (right).

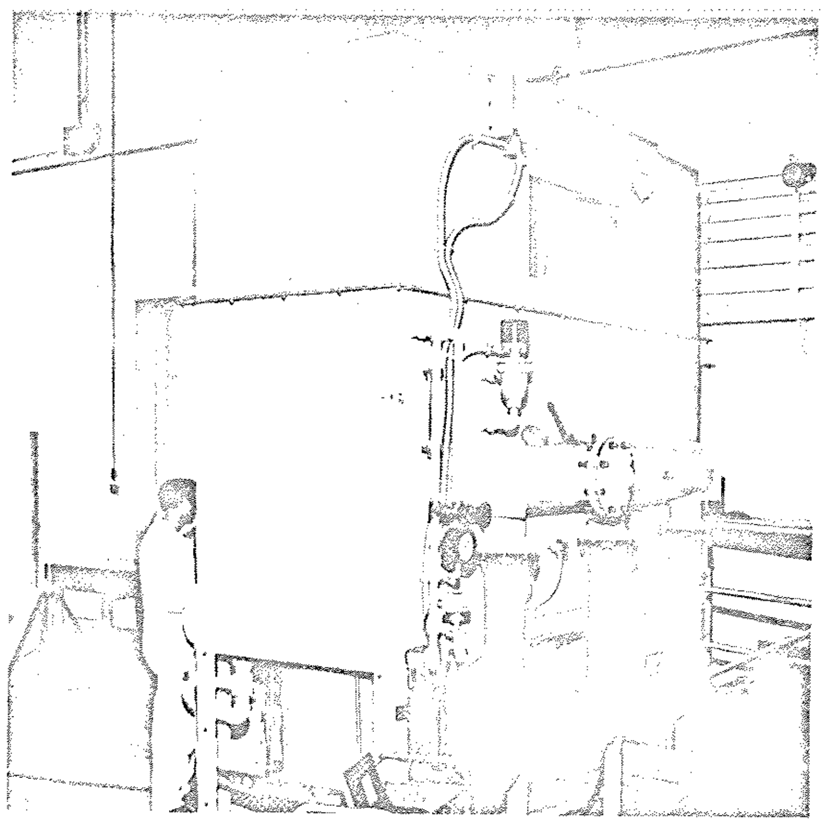


Fig 10—Liquid rheostat must be able to handle 10% more power than the 30-min rating of the motor, and a dissipation rate of not less than 7000 hp continuously. Liquid-to-liquid heat exchanger behind rheostat removes the heat directly from the electrolyte. See Fig 9 for electrode drive arrangement.

ABOUT OUR AUTHOR

This month's cover shows our author, Clement S. Daly, checking the slip-ring assembly of a 1450-hp synchronous motor that drives the d.c. generator that drives the 1250-hp auxiliary-drive starting motor. Big drives have been Mr. Daly's business for a long time. He has been with Calspan Corporation, Buffalo, since 1947.

Calspan Corp. is an independent research and development organization that performs science and engineering programs for government and industry. Its fields: Aerosciences, electronics, avionics, computer sciences, transportation and vehicle research, and the environmental sciences.

Mr. Daly is Head, Equipment and Fabrication Branch. He supervises design, fabrication, new-equipment selection, installation, operation, maintenance, and upgrading of electrical, hydraulic, and mechanical equipment for several test facilities—facilities like the 8-ft transonic tunnel he discusses here, plus a propeller dynamometer, a wave superheater, a one-square-foot wind tunnel, several shock tunnels, and an atmospheric-simulation facility.

And these and other facilities made him responsible for support systems including a 50,000-kva transformer and switchgear yard, a 30,000-psi, 1-1/2-million-cu-ft gas storage and distribution system, and vacuum systems and cryogenic systems. His tasks cover cooling and heating systems, and gas filtering, recovery, and drying systems.

Recently, he was involved in developing concepts for an a.c.-third-rail supply system for a mass-transit guideway test facility at Calspan, and a test facility for auto, truck, and bus tires.

Mr. Daly is a member of several Calspan committees concerned with safety and personnel management, a member of the Institute of Electrical and Electronics Engineers, and a registered engineer in the state of New York.

Driving the compressor—The output shaft of the drive system connects to a speed increaser through a cast-steel flexible coupling rated at 5120 hp per 100 rpm. The single-stage herringbone increaser (Fig 11) has a speed-increase ratio of 4.218:1.

The speed increaser connects to the axial-flow compressor by means of a forged-steel flexible coupling rated at 960 hp per 100 rpm. The compressor is an 8-stage, fixed-blade machine. With speed adjustment, it can deliver up to 600,000 cfm and a range of pressure ratios to 3.50:1 at inlet pressures from 1.9 to 14.7 psia. The compressor housing is a section of the air duct, and the motors and speed increaser are outside the duct. A carbon face seal is provided where the compressor shaft extends through the housing. Three carbon segments interlock to form a ring. The ring housing is spring-loaded for face-seal pressure, and sealed by O-rings.

To start the auxiliary drive, the d.c. motor accelerates the compressor to about 1/3 speed. Then a current-sensitive relay in the d.c. circuit closes the circuit breaker for the 13,000-hp wound-rotor motor. With both motors on line, an automatic load transfer takes place, and the wound-rotor motor picks up the greater share of the load.

As drive speed continues toward 570 rpm, the wound-rotor motor and the d.c. starting motor share load automatically and, at full speed, both machines carry full-rated or overload-rated load.

Here's how automatic load transfer works:

As system load varies, the d.c. motor immediately senses a speed change. As the d.c. motor tries to hold constant speed, its current changes. A d.c.-current-sensitive instrument senses the change and sends a signal to the liquid rheostat, calling for an electrode position change. The electrode position change affects wound-rotor current and, therefore, wound-rotor-motor load-carrying capacity, such that the load-sharing ratio is correct.

To stop the drive, the wound-rotor motor disconnects immediately from the line, and the d.c. motor provides regenerative braking.

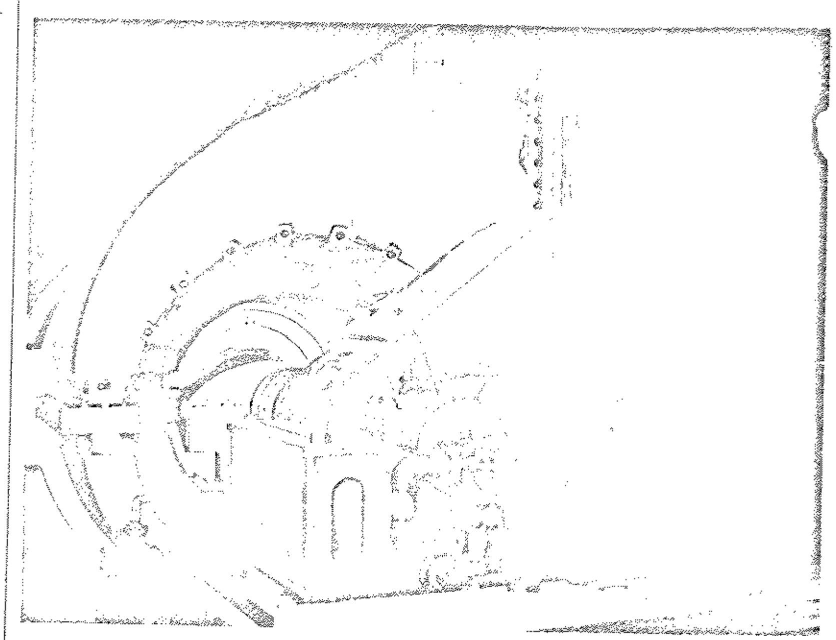


Fig 11—Auxiliary-drive speed increaser before installation in drive line. Input shaft is in foreground; compressor in back. Increaser rating is 12,000 hp with input and output speeds of 570 and 2404 rpm, respectively.

The auxiliary system needs no special couplings in the drive because motors, speed increaser, and compressor mount on a common concrete base. Offset and angular misalignment are slight. The compressor connects to the large air duct with 8-ft-diameter expansion rings. Compressor air inlet temperature varies between 80 and 120 F, and exhaust temperature approaches 375 F. For those tests that don't need the axial-flow compressor, an 8-ft rubber-sealed butterfly valve upstream and a similar 6-ft valve downstream seal it out of the main air circuit.

Once around—The total power input to Calspan's 8-ft, variable-density transonic tunnel can be well above 30,000 hp when you count support systems along with air-moving systems. For an installation of this size, many problems can arise. The designer must catch them in the design stage. Substitution, modification, and rework are too large and costly to serve as crutches for a weak design.

The designer must make a thorough study of the performance expected, the system's maintainability, and the life requirements. That approach has assured Calspan's transonic tunnel of successful performance of everything expected of it for many years.

Suppliers: Main-drive motors by Ateliers de Constructions Electriques de Charleroi, Belgium. Auxiliary drive motors and liquid rheostat by General Electric Co., Schenectady. Main-drive motor-generator control, m-g motor, Westinghouse Electric Corp., Pittsburgh. M-g set d.c. generator by General Electric Co., Schenectady. Fan-hub self-aligning radial and thrust bearings by SKF Industries, Philadelphia. Main-drive floating-shaft coupling, and auxiliary-drive motor-to-increaser and increaser-to-compressor couplings by Koppers Co., Inc., Power Transmission Dept., Baltimore. Hub quick-disconnect coupling by Western Gear Corp., Belmont, Calif. Speed increaser by Farrel Co. Div., USM Corp., Gear Div., Ansonia, Conn.